

LATTICE FIELD THEORY BEYOND THE STANDARD MODEL

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Boston University

USQCD Hardware Review, FNAL, May 15-16, 2014

BSM GROUPS IN USQCD

Argonne: J. Osborn, D. Sinclair

Boston: R. Brower, M. Cheng, C. Rebbi, E. Weinberg, O. Witzel

BNL: M. Lin, S. Syritsyn

Colorado: A. Cheng, T. DeGrand, A. Hasenfratz, Y. Liu, E. Neil, G. Petropoulos

Livermore: E. Berkowitz, E. Rinaldi, C. Schroeder, P. Vranas, J. Wasem

Oregon: G. Kribs

Pacific: K. Holland

RPI: J. Giedt

Syracuse: S. Catterall, D. Schaich, A. Veernala

U. Washington: M. Buchhoff

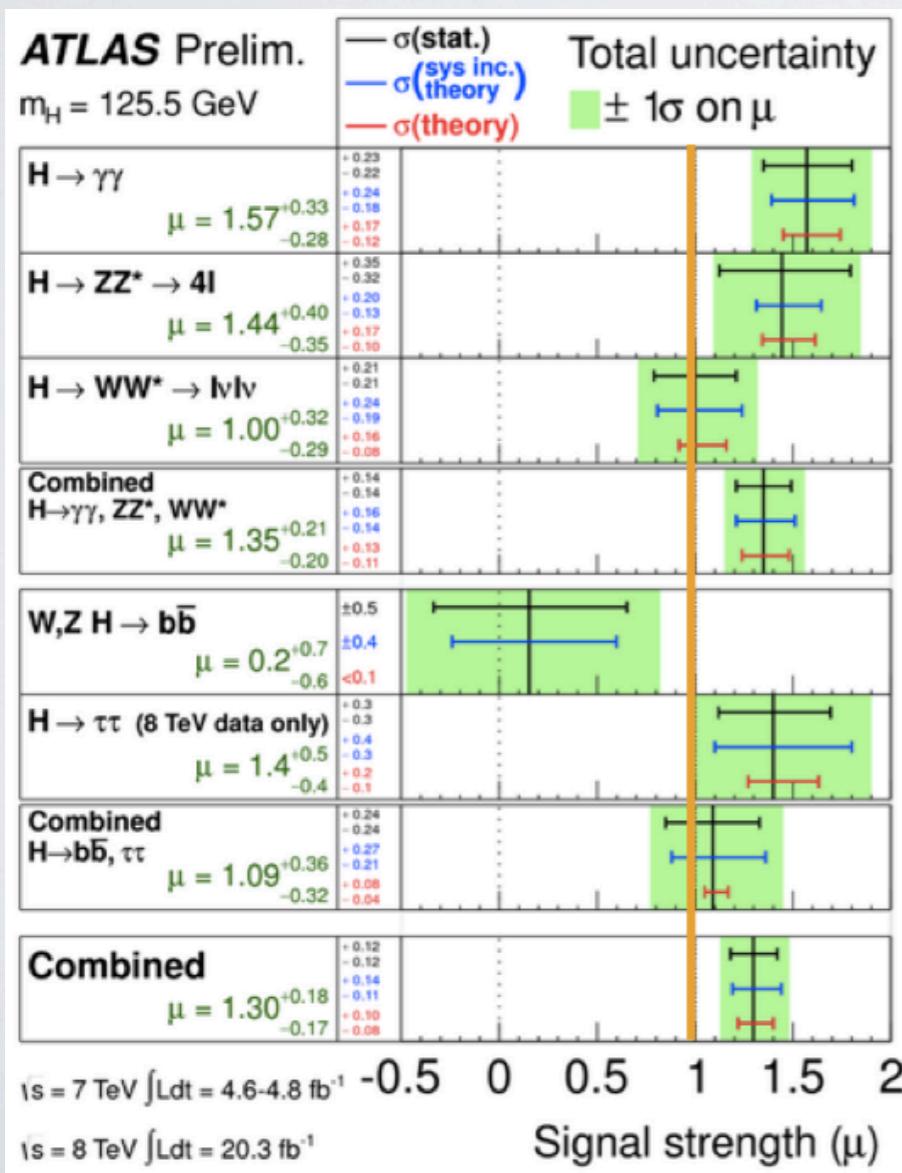
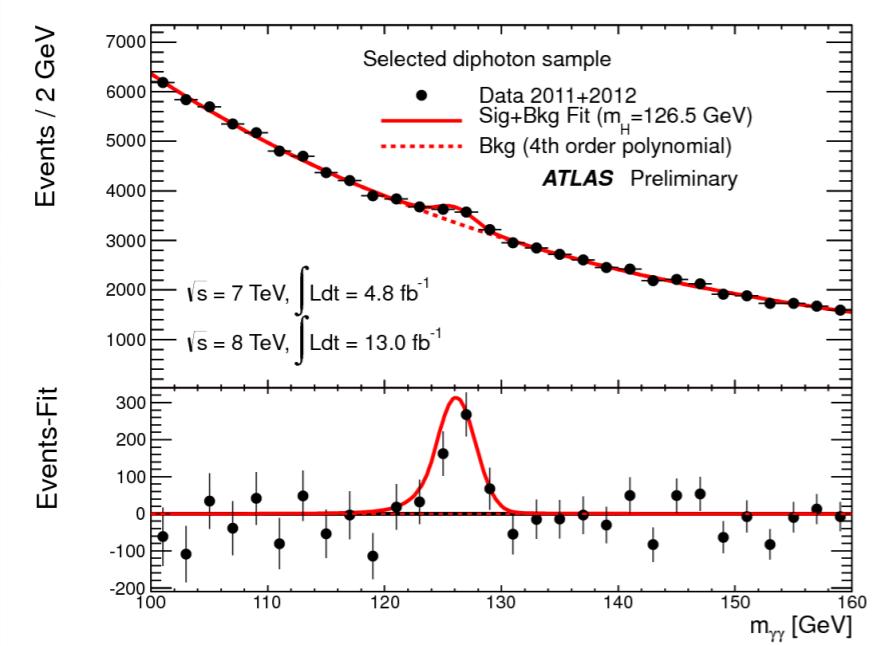
UC Davis: J. Kiskis

UCSD: J. Kuti, R. Wong (Z. Fodor and D. Nogradi)

Yale: T. Appelquist, G. Fleming, G. Voronov

collaborations:
LSD LHC LSUSY

approx 1/4 active USQCD population !



Higgs is found but what next?

The SM most likely just an “effective theory”. Trivial without an UV cut-off.

An elementary SM Higgs is like

- SuperConductivity without BCS pairs!
- Soft pions without QCD quarks!

But exploring Higgs physics is CHALLENGING!

Need to combine all available tools!

- Experiments at higher energy
- Experiments at higher precision
- Better theory of strongly coupled quantum field theory: Lattice or AdS?

INTRODUCTION

Paradox of our age*:
The Nature of the unnatural Higgs?

* “a riddle, wrapped in a mystery, inside an enigma”

Winston Churchill October 1959

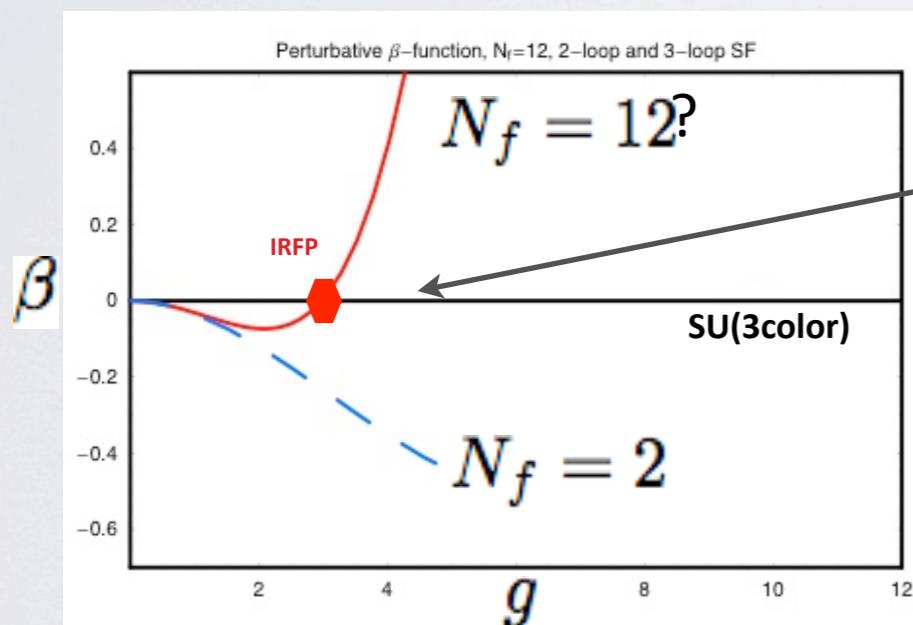
A bound state of strongly interacting “fermions”?

BUT ISN'T TECHNICOLOR DEAD? YES!

However, generic composite models and new strong dynamics are much less constrained.

Model builders just guess at the dynamics!

Lattice Gauge Theory is only rigorous tool for strongly interacting quantum physics.



We know that IR conformal fixed points do appear when you add many light flavors

$$L \frac{\partial}{\partial L} g(L) = \beta(g) \xrightarrow{g \rightarrow 0} b_0 g^3 + b_1 g^5 + b_2 g^7 + \dots$$

$$b_0 = -\frac{1}{(4\pi)^2} \left(\frac{11}{3} N_c - \frac{2}{3} N_f \right), \quad b_1 = -\frac{1}{(4\pi)^4} \left[\frac{34}{3} N_c^2 - \left(\frac{13}{3} N_c - \frac{1}{N_c} \right) N_f \right].$$

Physics of near conformal theories is NOT scaled up QCD!!

What are the options?

- **New symmetries** are needed to stabilize a scalar against (quadratic) UV divergences (below the Planck mass).
 1. Low mass **Dilaton** mode in a near (walking) IR conformal theory
(scale symmetry from partial conserved Dilaton current?)
 2. Low mass **Pseudo Nambu Goldstone Boson**
(EW global symmetry)
 3. **SUSY** -- low scale susy is on life support ?
(susy/shift symmetry)

PSEUDO-DILATON HIGGS

Spontaneous breaking of approximate scale invariance ?

$$\partial_\mu D_\mu(x) = T_\mu^\mu = \frac{\beta(\alpha)}{4\alpha} F_{\mu\nu}^a F_{\mu\nu}^a \quad \langle 0 | \partial_\mu D_\mu | \sigma \rangle >= f_\sigma m_\sigma^2$$

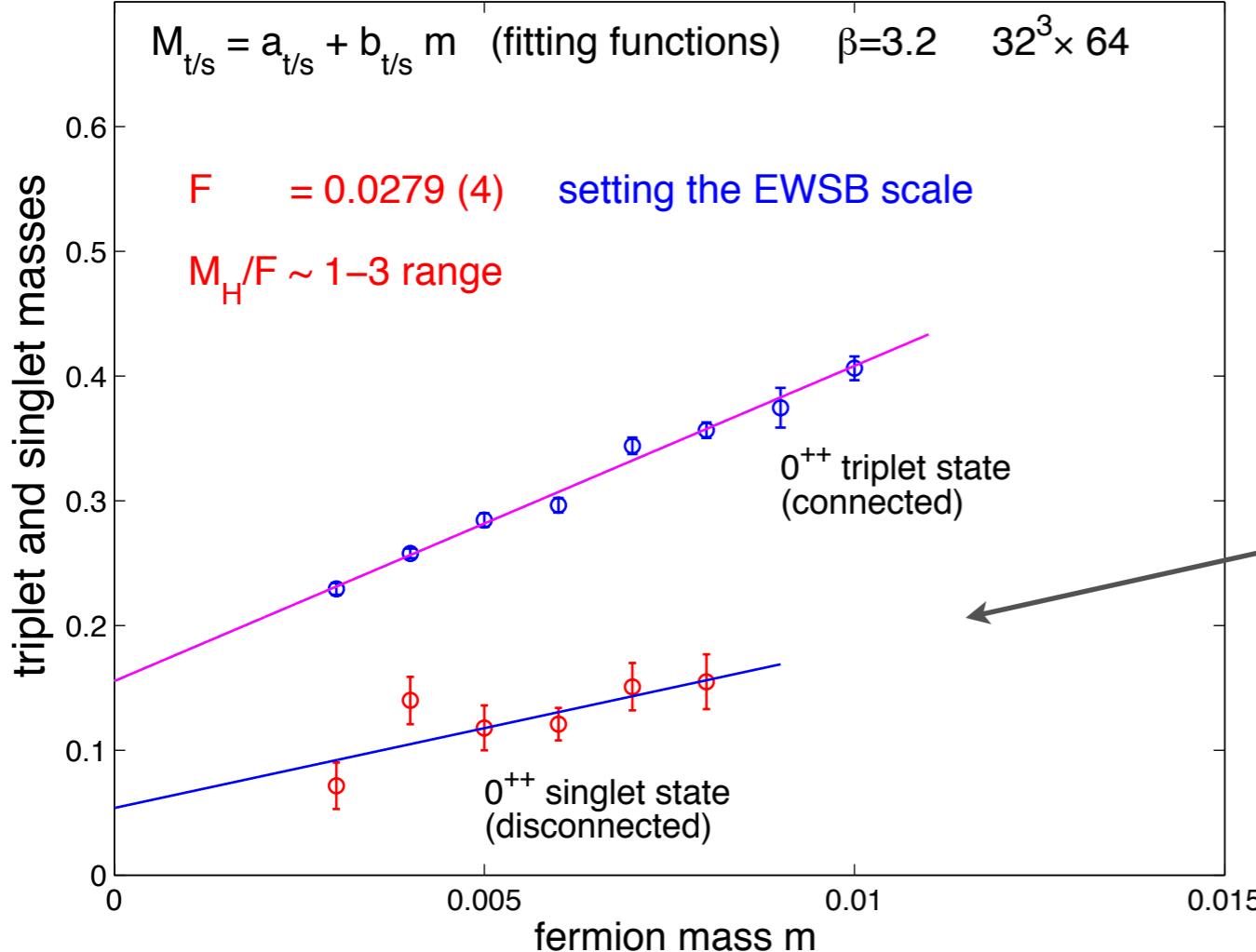
Parametrically light 0++ scalar? (Higgs?)

$$m_\sigma / f_\sigma \rightarrow 0?$$

Pseudo-Dilaton:
“Revolutionary” new Goldstone-like mechanism?

LIGHT SCALAR IN SEXTET MODEL ?

Triplet and singlet masses from 0^{++} correlators



top quark loops suppress Higgs mass

$M_p/F \sim 7$
 $M_p \sim 1.75$ TeV
LHC14?

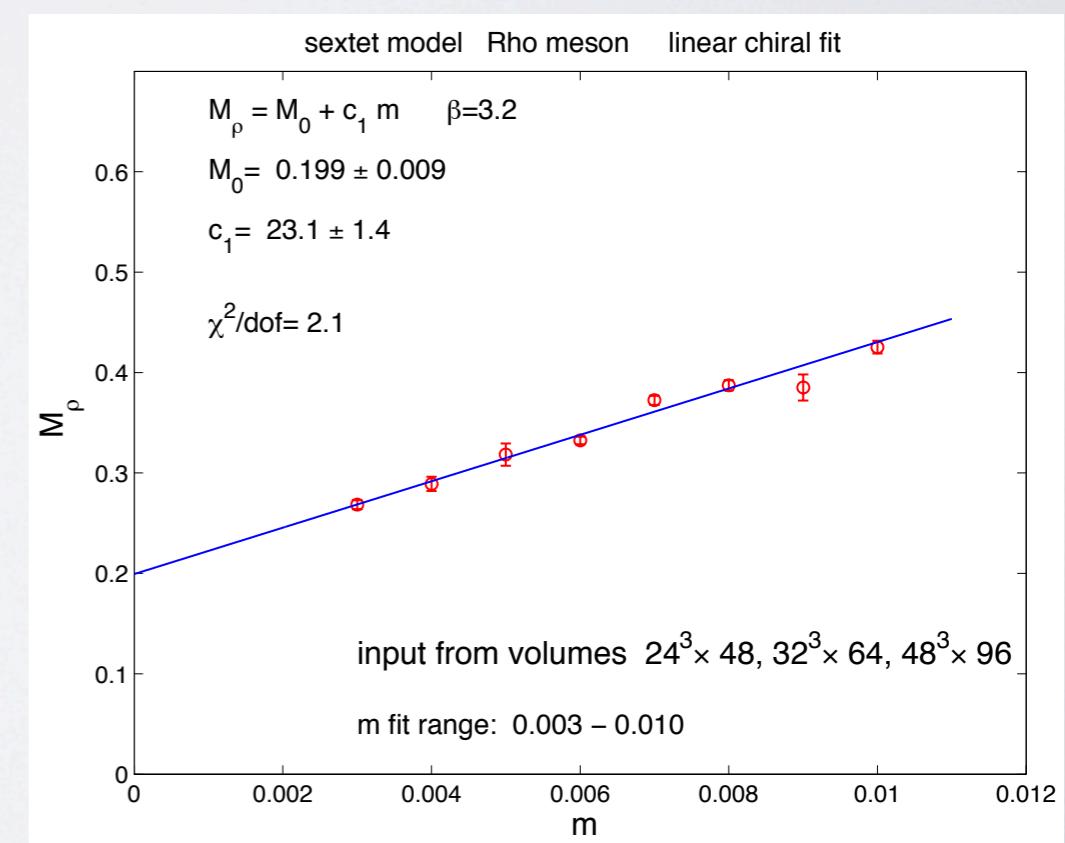
[Zoltan Fodor](#), [Kieran Holland](#), [Julius Kuti](#), [Daniel Nogradi](#), [Chik Him Wong](#)

Can a light Higgs impostor hide in composite gauge models?

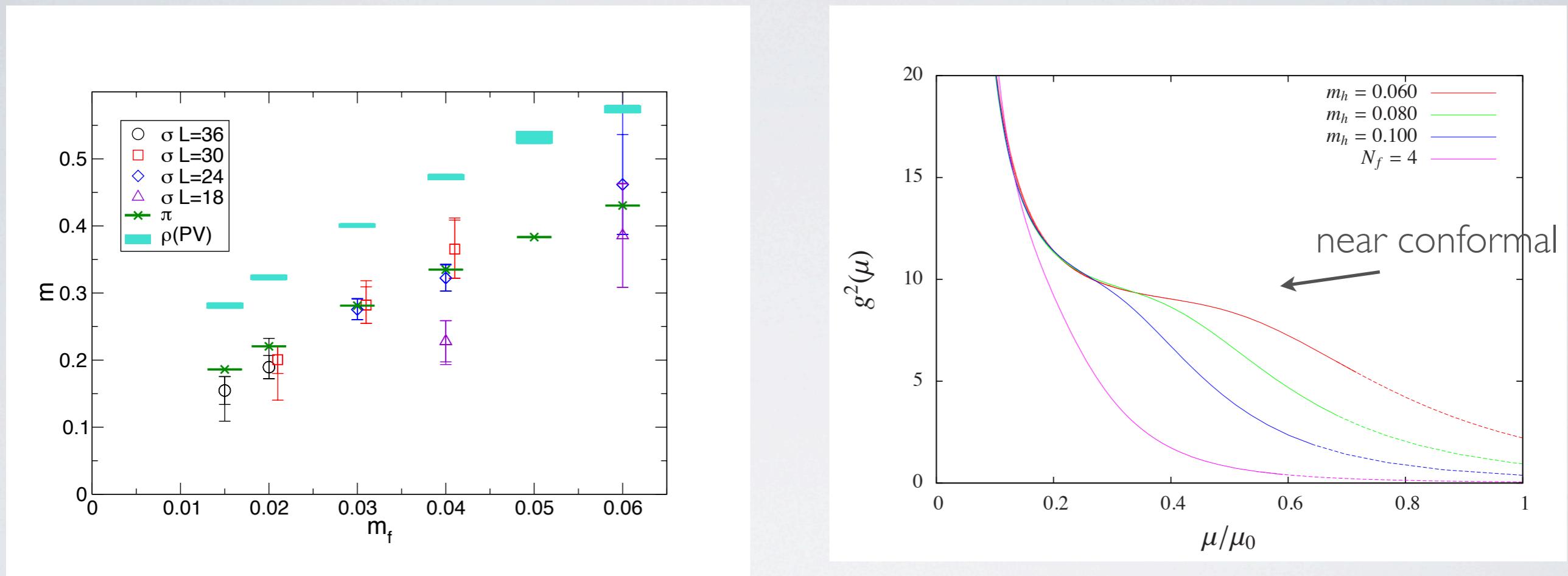
<http://arxiv.org/abs/1401.2176>

SU(3) color $N_f = 2$ two-index symmetric(sextet) fermions

Disconnected diagrams important also mixing with 0^{++} glueballs ...



8 Flavors Fundamental SU(3)



$$m_\sigma \sim m_\pi$$

LatKMI: <http://arxiv.org/abs/1403.5000>

4+ 8 Wilson flow coupling
BU/Bolder: raising 8 masses

Tentative conclusion: near conformal theories may exhibit a light scalar that could play role of the Higgs ..

PSEUDO GOLDSTONE SCALAR

UV completion of the Little Higgs Phenomenology



MINIMAL PNGB PROJECT:

SU(2) with Nf=2 (EW gauged) fermions in fund rep.
Minimal model of this type

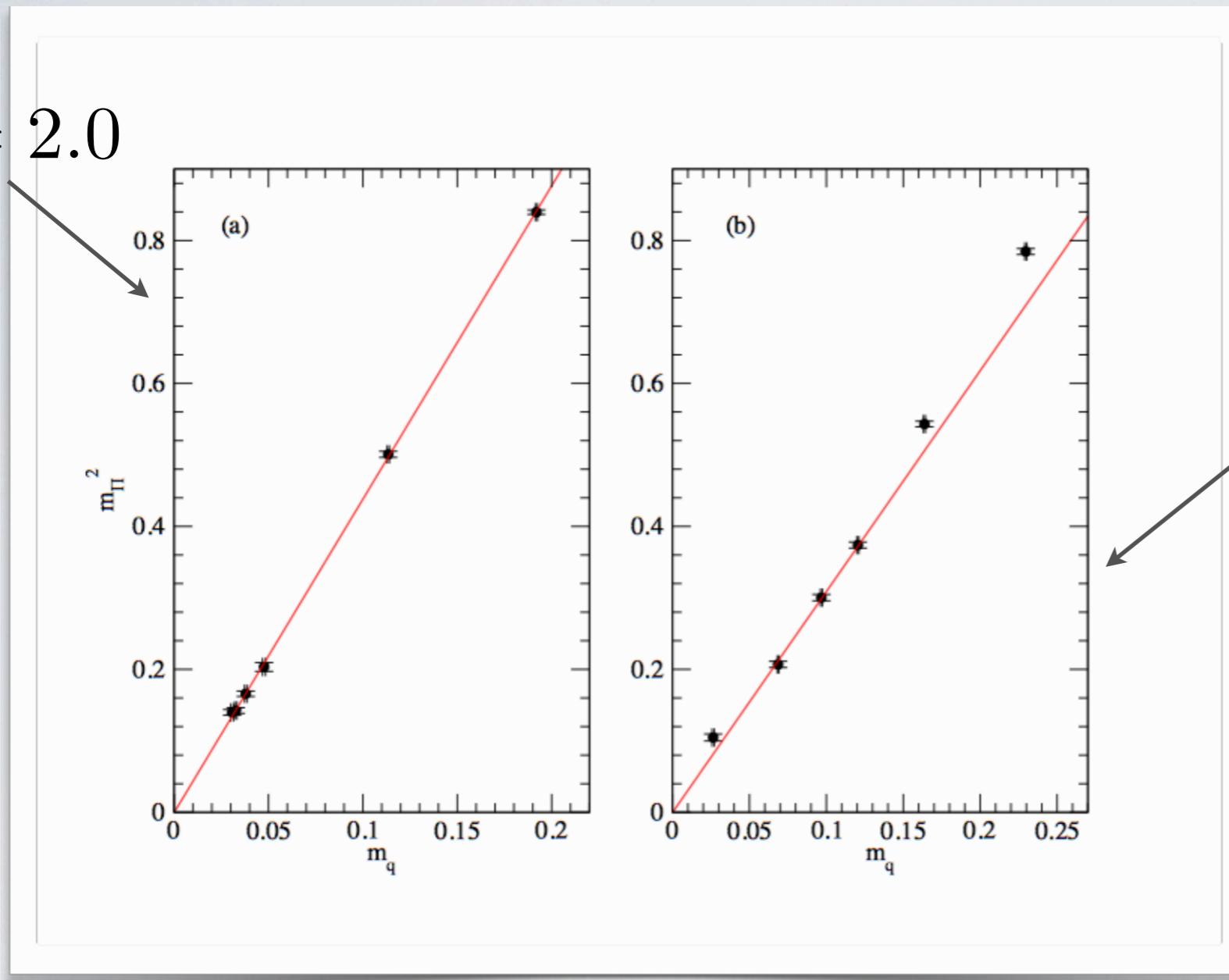
Chiral symmetry enhances to SU(4). MAC (Most Attractive Channel) symmetry breaking: $SU(4) \rightarrow Sp(4)$

5 GBs. 3 pseudoscalars give mass to W,Z.

Remaining 2 scalars yield Higgs and a dark matter candidate.

In code development and optimization stage by LSD using SciDAC-3 FUEL software & GPUs

GOLDSTONES FOR MINIMAL SU(2) PNGB MODEL



The Goldstone boson mass squared as a function of the PCAC quark mass for (a) $\beta = 2.0$ and (b) $\beta = 2.2$.

5 degenerate GB (Sannino et al. arXiv:1109.3513)

pion $\bar{u}d$
scalar ud

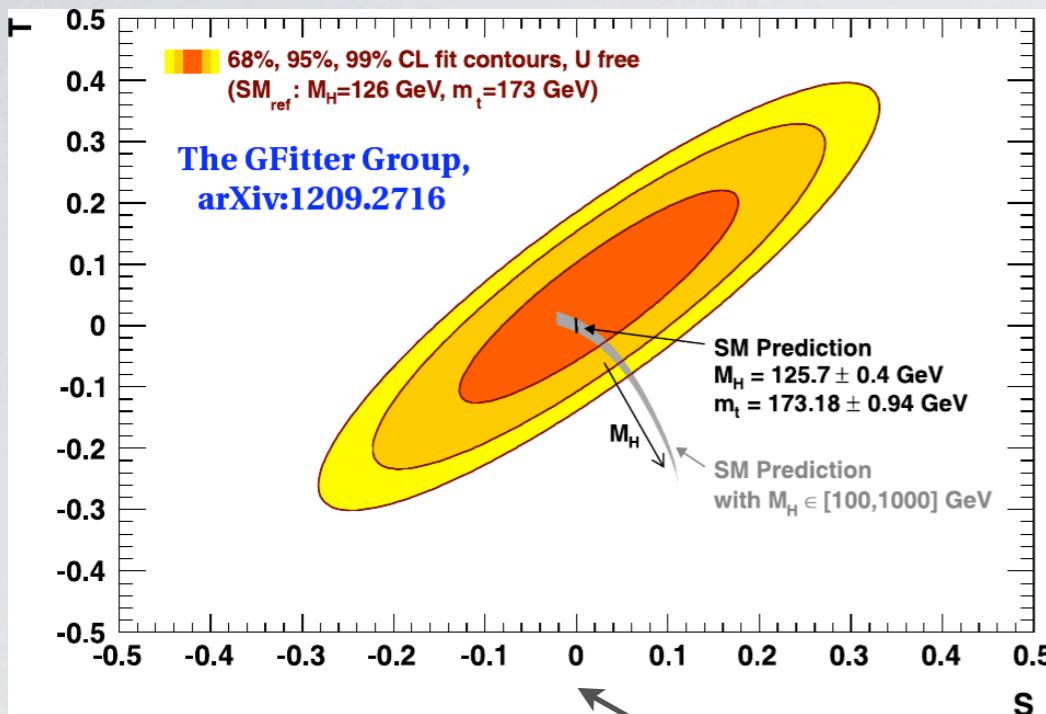
$\beta = 2.2$

Current US Effort is on Software & algorithms add mass & 4 fermi terms to lift masses of remaining 2 scalars

HIGHLIGHTS OF US BSM

- First calculations of S parameter (PRL 106: 231601 (2011))
- First calculation of parameters needed for WW scattering (PRD 85:074505 (2012))
- First studies to provide evidence for conformality of SU(2) with Nf=2 adj. fermions (JHEP 0811 (2008) 009)
- First calculation showing a light scalar composite scalar close to the conformal window (PoS LATTICE 2013, 062 (2013))
- First calculation of gaugino condensate in N=1 SYM (PRD 79 025015 (2009))
- First determination of phase diagram of N=4 SYM (JHEP 11 072 (2012))

HIGHLIGHTS - S PARAMETER

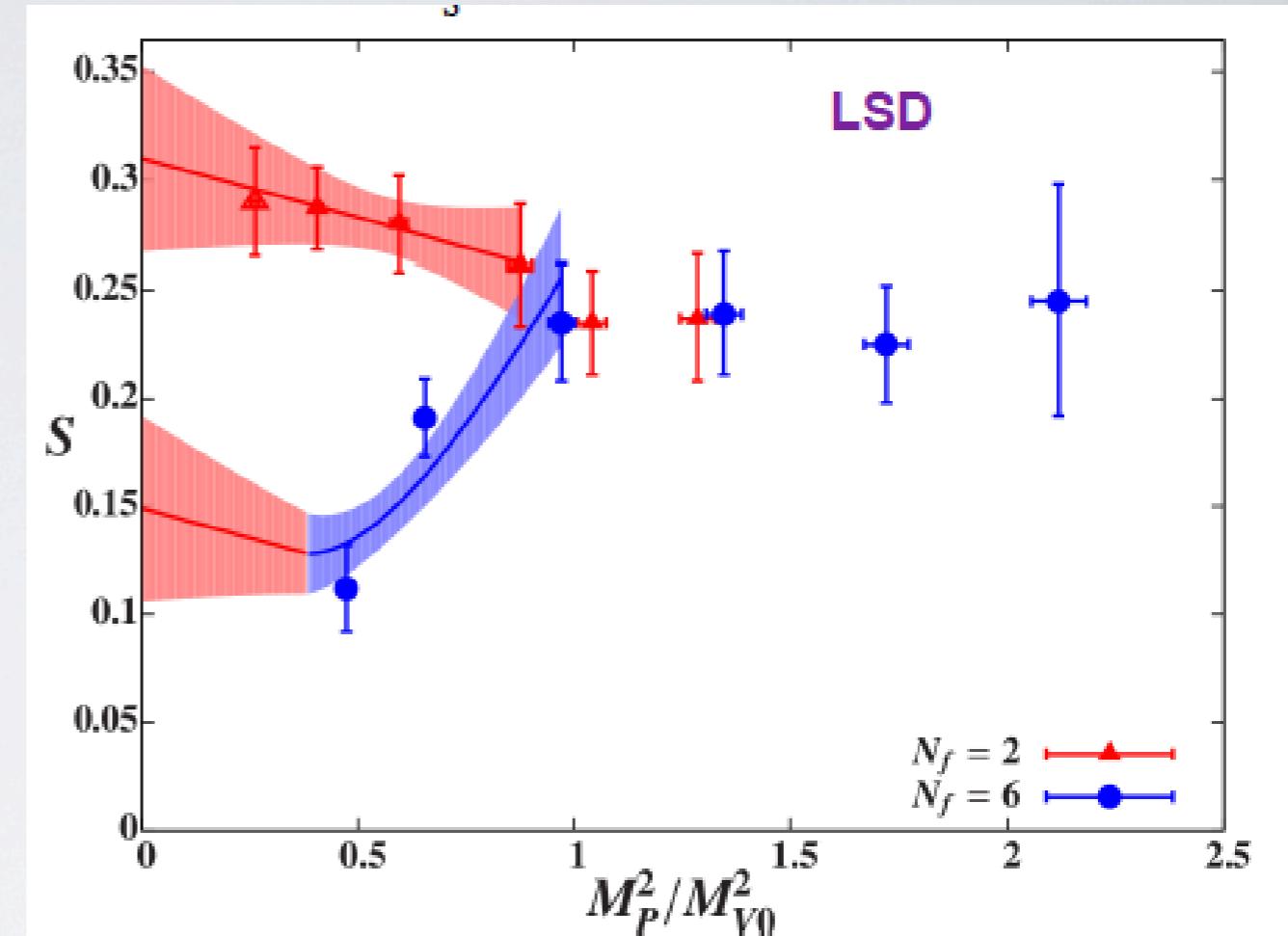


S parameter put strong constraint on compositeness.

Determined from vacuum polarization of W,Z bosons. Can be computed on lattice

S parameter drops over naive QCD scaling as Nf increases

Apparently S parameter of near conformal models small due to near chiral restoration? (e.g. rho/A1 degeneracy)



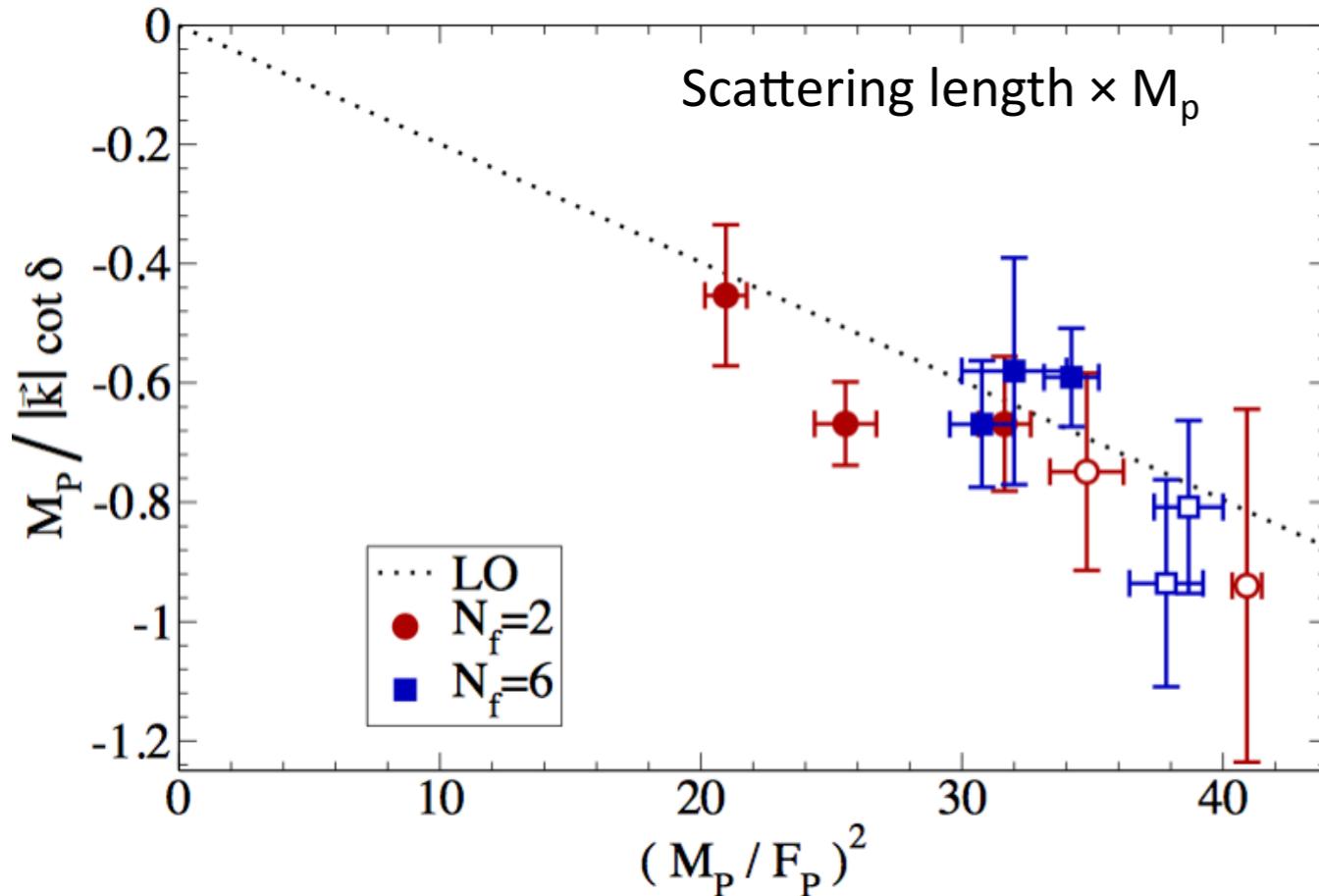
Experiment: S is close to zero

LSD collab

Thomas Appelquist, Ron Babich, Richard C. Brower, Michael Cheng, Michael A. Clark, Saul D. Cohen, George T. Fleming, Joe Kiskis, Meifeng Lin, Ethan T. Neil, James C. Osborn, Claudio Rebbi, David Schaich, Pavlos Vranas

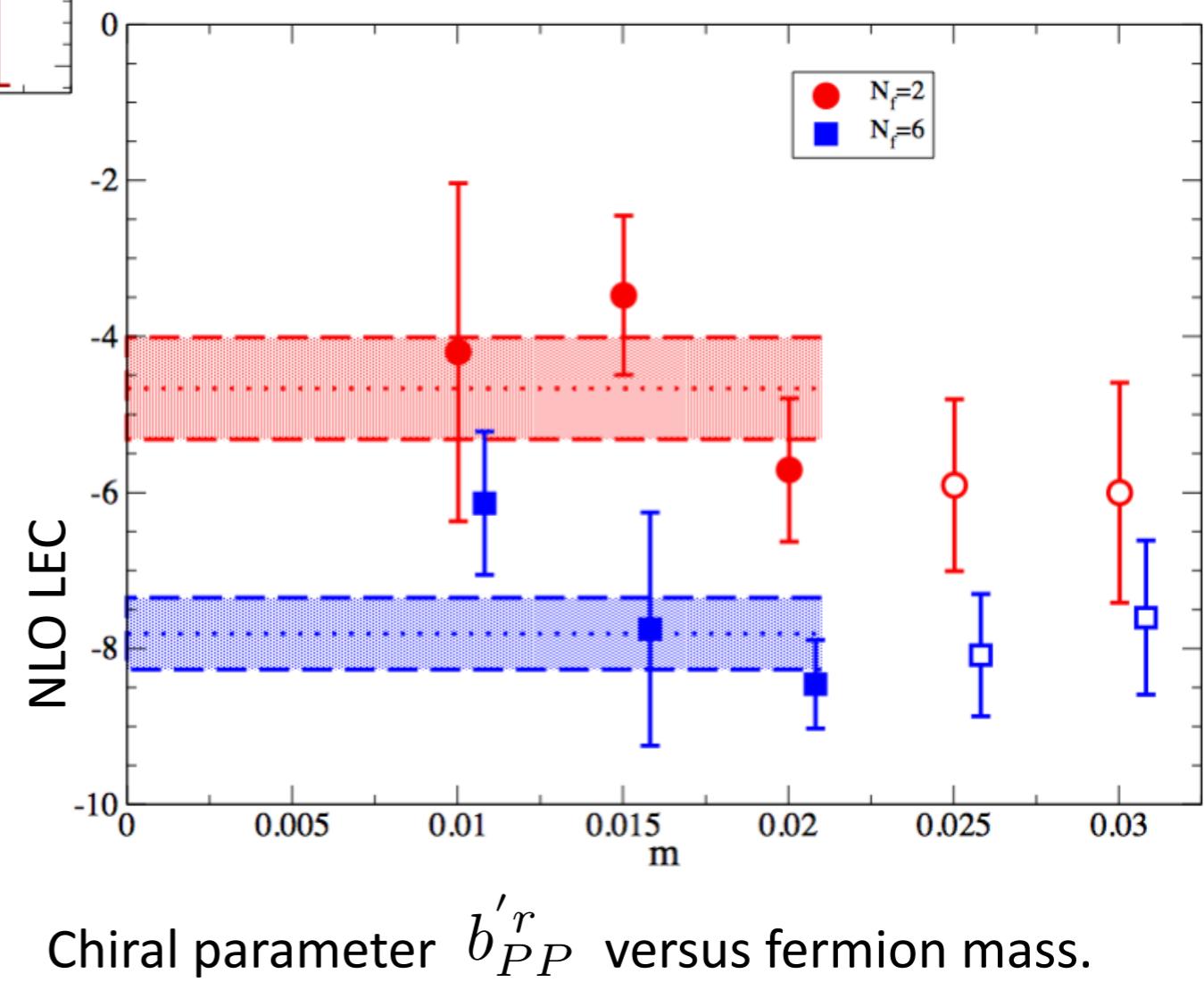
<http://arxiv.org/abs/1009.5967>

HIGHLIGHTS - WW scattering from the lattice



SU(3c) $\pi\pi$ scattering in the maximal isospin channel

LSD:<http://arxiv.org/abs/1201.3977>



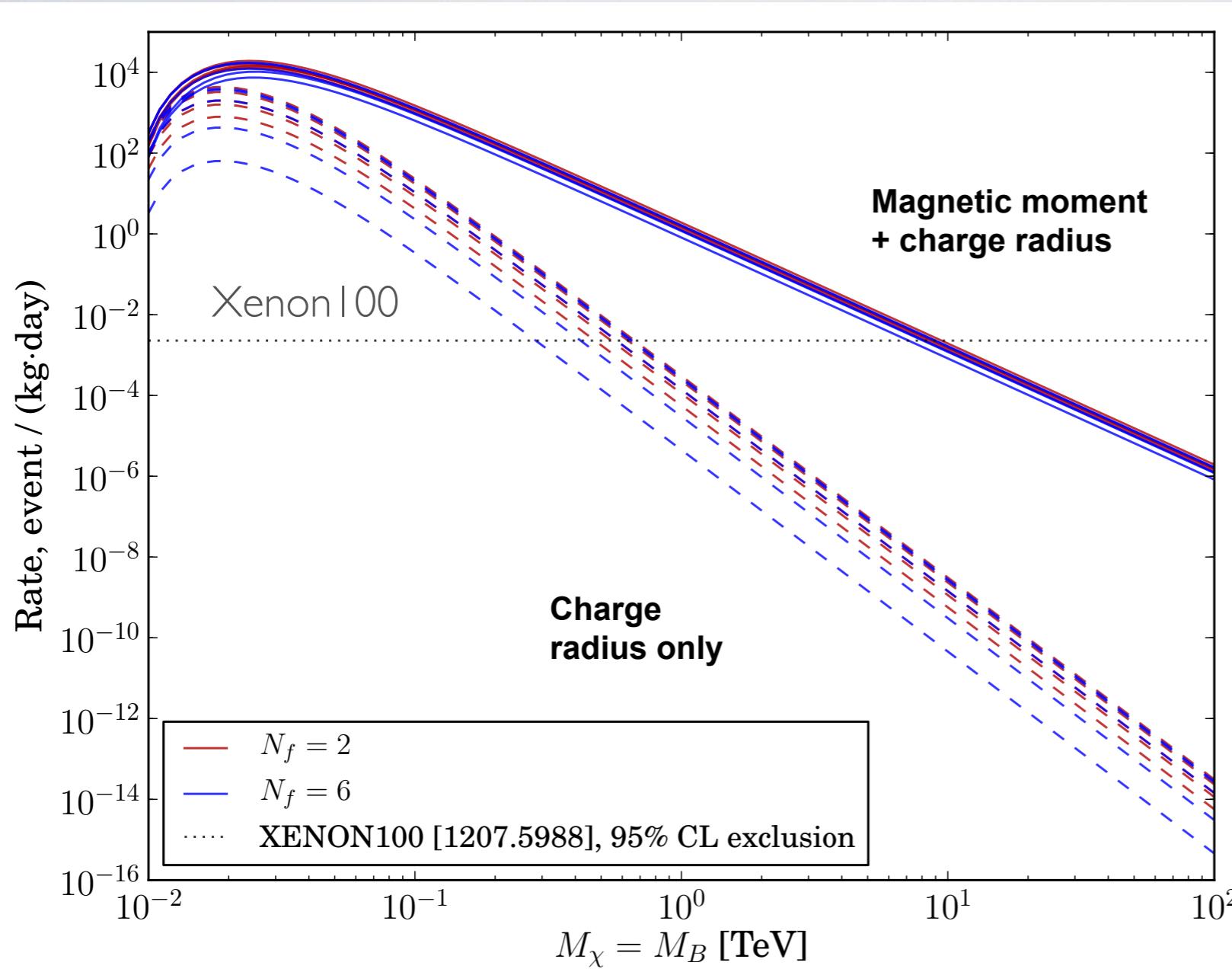
- NLO LECs differ between 2f and 6f

- Estimates can be made for WW scattering parameters

$$\begin{aligned} \tilde{\alpha}_4(M_H) + \tilde{\alpha}_5(M_H) &= (3.34 \pm 0.17^{+0.08}_{-0.71}) \times 10^{-3} \\ &\quad - \frac{[\log \frac{M_H^2}{F^2} + O(1)]}{128\pi^2} \end{aligned}$$

Chiral parameter b_{PP}' versus fermion mass.

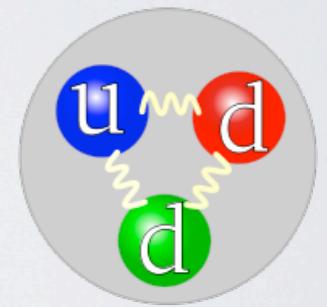
HIGHLIGHTS - DARK MATTER CANDIDATES



Composite models generically produce new stable baryons – candidates for asymmetric DM

Sample calc of EM form factors for electroweak neutral dark matter baryons in 3 color theory (LSD)

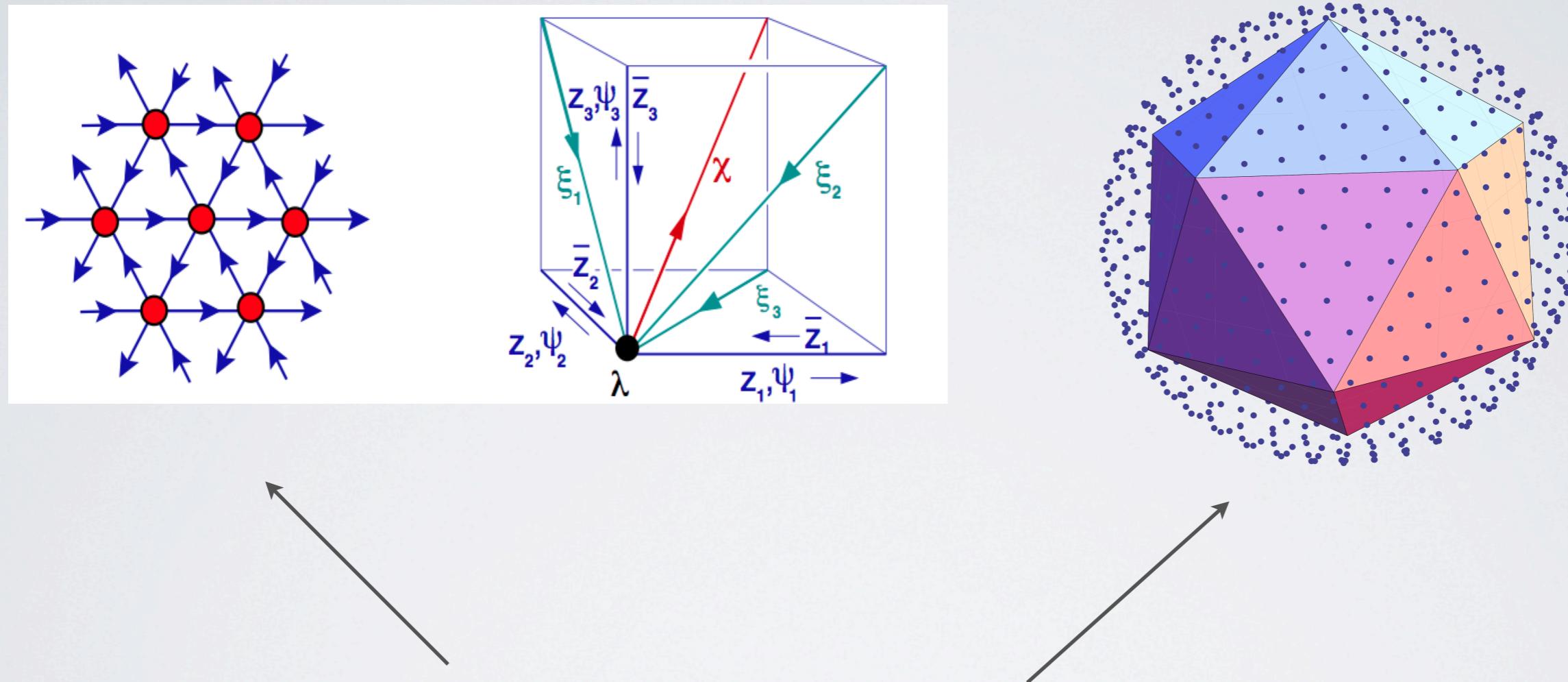
lightest



Generate x-sections for DM nucleon interactions. Use with Xenon100 to exclude DM with mass < 10 TeV. LUX experiment 3x stronger bound.

LSD <http://arxiv.org/abs/1402.6656>

NEED TRULY NOVEL METHODS!



Lattice SUSY & Lattice Radial Quantization
& Maldacena's AdS/CFT Strong Coupling

SUSY - $\mathcal{N}=4$ SUPER YANG-MILLS

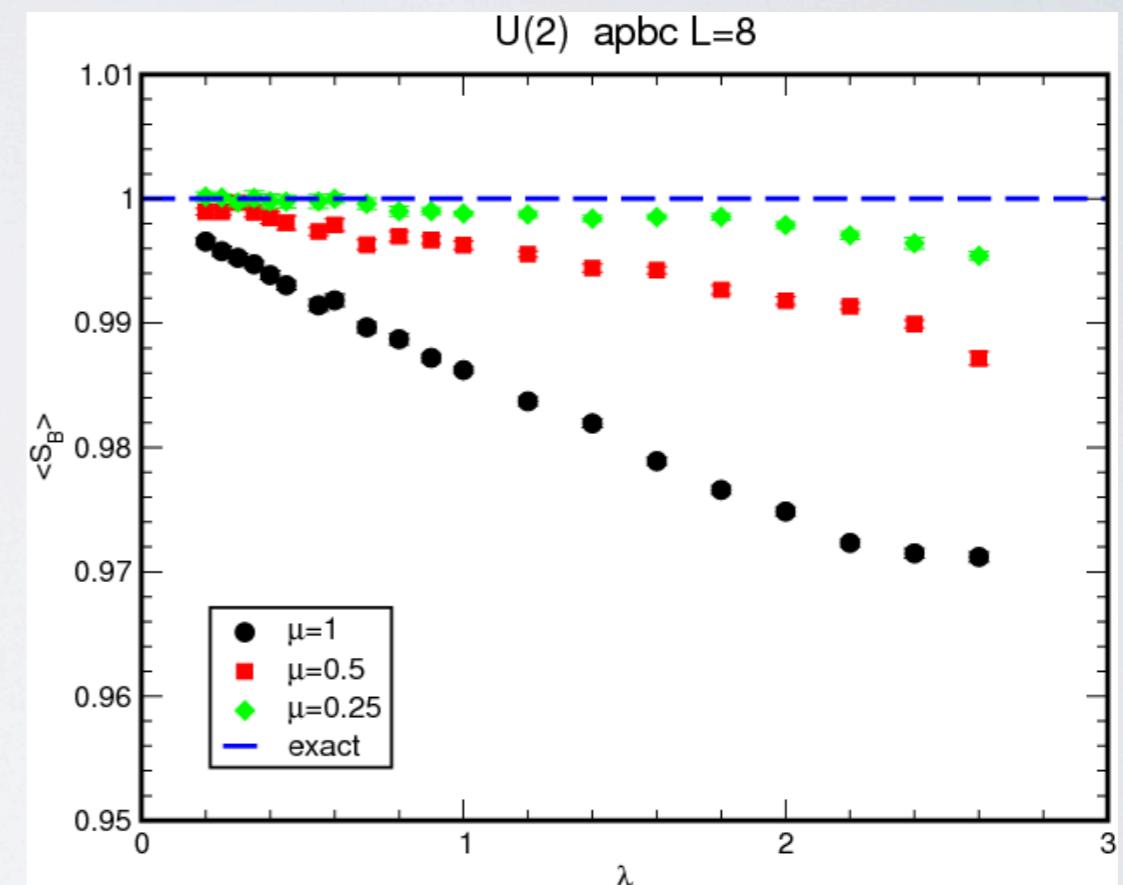
Recent developments (led by USQCD) led to a lattice formulation of $N=4$ SYM that preserves (some) SUSY

Reduces/eliminates fine tuning problem

Flat directions protected - explicit dilaton from translations ... Prototype CFT.

Connections to AdS/CFT holographic models.

Exact SUSY Ward identity satisfied for vanishing scalar mass



$$\lambda_{lat} = g^2 N$$

Lattice Radial Quantization

$$H = P_0 \text{ in } t \implies D \text{ in } \tau = \log(r)$$

$$ds^2 = dx^\mu dx_\mu = e^{2\tau} [d\tau^2 + d\Omega^2]$$



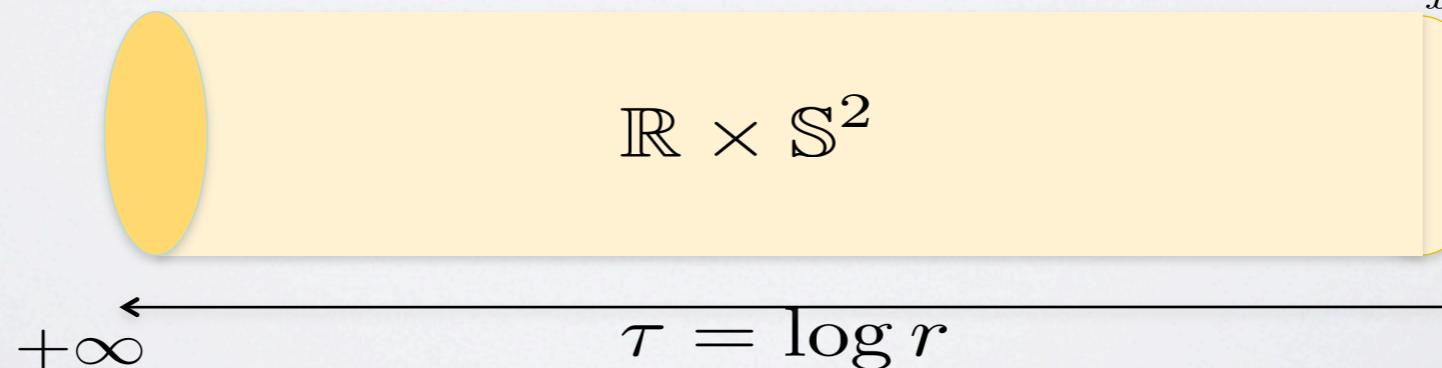
Conformal Map : $\mathcal{R}^d \rightarrow \mathcal{R} \times \mathcal{S}^{d-1}$

"time" $\tau = \log(r)$, "mass" $\Delta = d/2 - 1 + \eta$

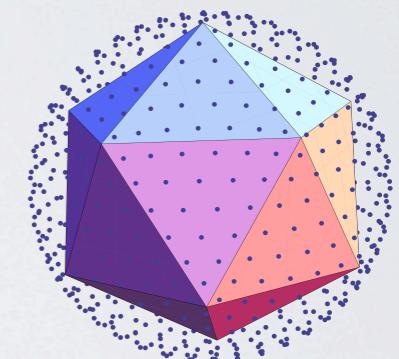
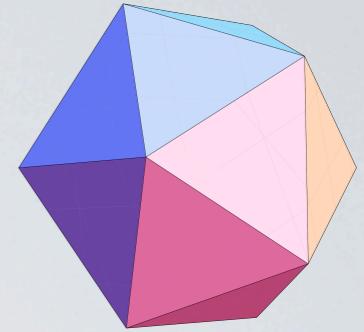
Have an exponentially large lattice to separate

$$a < \Delta r < L \quad \text{vs} \quad a < \Delta \log(r) < L$$

|st test
3D Ising

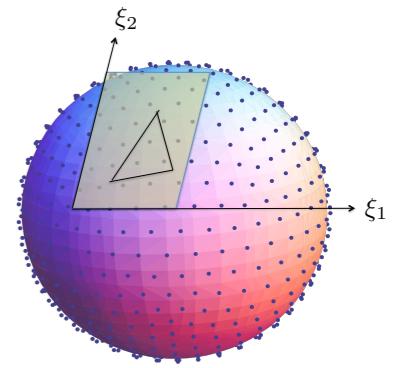


$$\begin{aligned} \lim_{x \rightarrow 0} \mathcal{O}(x)|0\rangle &= |\mathcal{O}\rangle \\ \text{state-op} & \\ (r = 0) & \\ -\infty & \end{aligned}$$



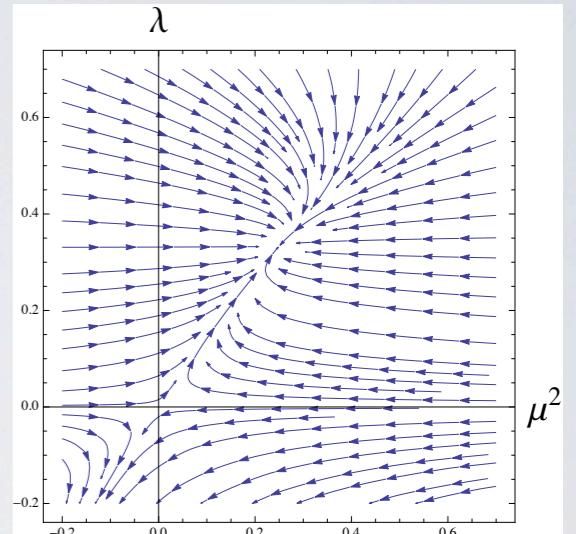
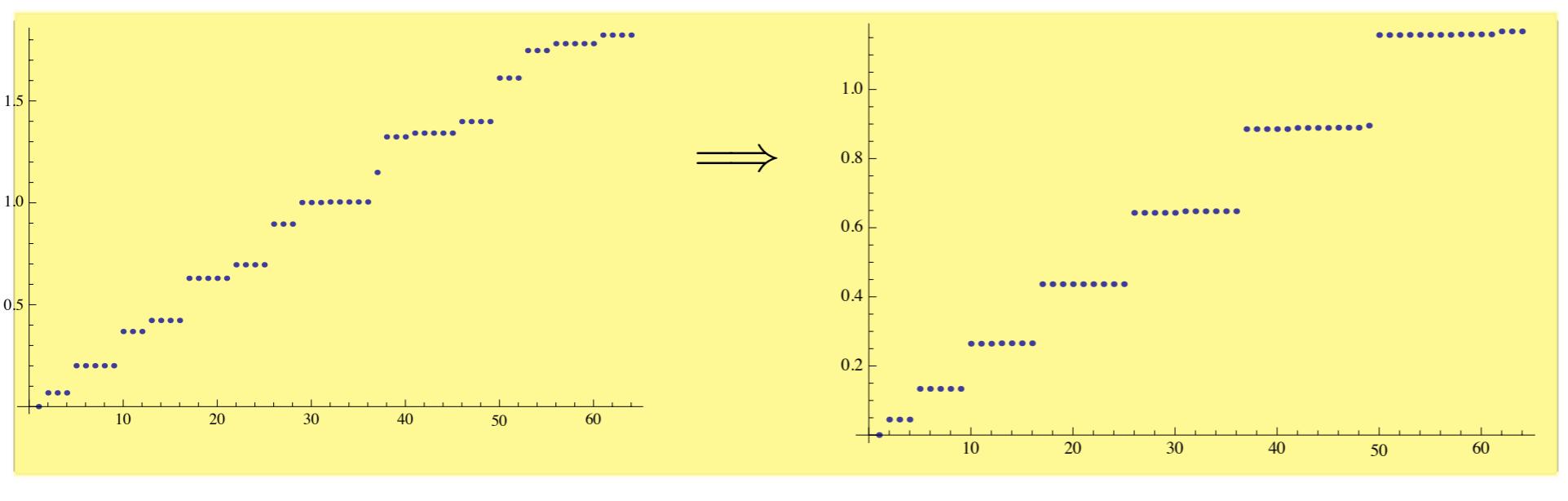
Finite Element Method/Regge Calculus*

How do you put a field theory lattice in curved manifold?



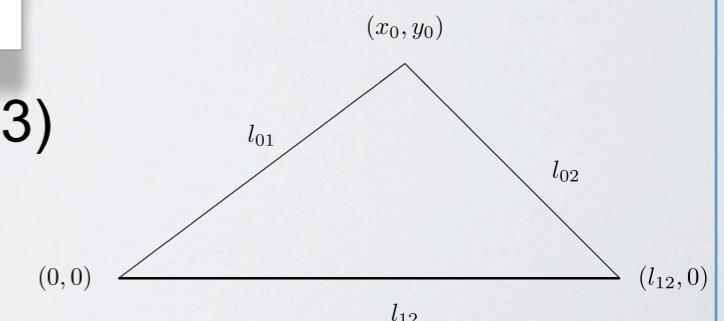
$$S = \int d^D x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \lambda (\phi^2 - \frac{\mu^2}{2\lambda})^2 \right].$$

$-\nabla^2 \implies (l + 1/4)^2$ for $m = -l, \dots, l$ spectrum on FEM sphere



$I = 0 (A), 1 (T1), 2 (H)$ are irreducible 120 Icosahedral subgroup of $O(3)$

$$\int_{A_{012}} dx dy \partial_\mu \phi(x, y) \partial_\mu \phi(x, y) = \frac{1}{2A_{012}} [(l_{01}^2 + l_{20}^2 - l_{12}^2)(\phi_1 - \phi_2)^2 + \text{cyclic}]$$



*see also Christ, Friedberg, Lee on “Random Lattice” NP (1982)

SUMMARY: Composite Higgs Lattice Field Theory Program

- I. Need new theoretical ideas, new algorithms in a balanced computational program. (Many tools exchanged with LQCD)
2. Find generic mechanism for a light scalar mass composite consistent with experimental EW precision constraints
3. Determine experimental signatures to guide search for compositeness. Develop effective* near CFTs in AdS space.
4. We need to get ready! LHC14 will search for new physics in both composite and SUSY scenarios.

* Goldberger, Grinstein & Skiba: "the Higgs or dilaton ?" PRL (2008). <http://arxiv.org/abs/arXiv:0708.1463>

BACK UP INFO

REFERENCES

USQCD BSM white paper:

Lattice Gauge Theories at the Energy Frontier,

T. Appelquist, R. Brower, S. Catterall, G. Fleming, J. Giedt, A. Hasenfratz, J. Kuti, E. Neil, D. Schaich
arXiv:1309:1206

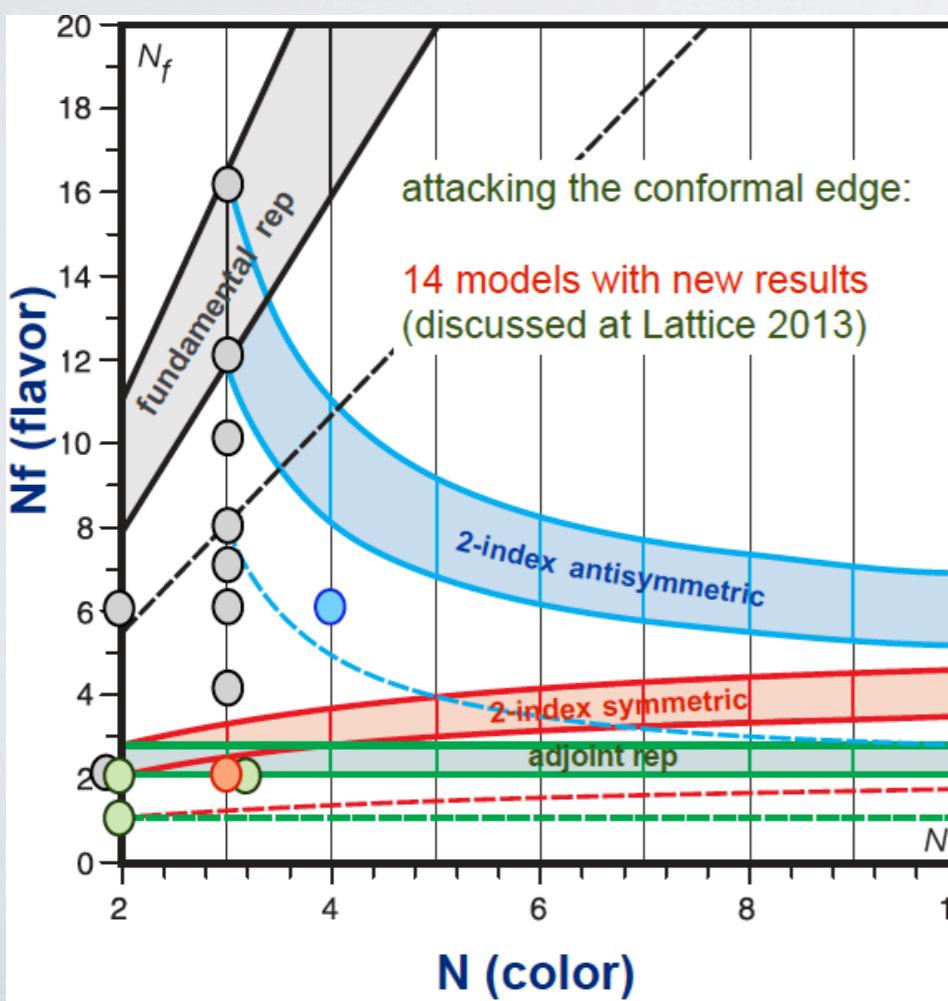
**Snowmass: Lattice field theory for the energy
and intensity frontiers, arXiv:1310:1607**

**“Lattice gauge theory and the Higgs boson”
plenary talk at LATTICE 13 by J. Kuti**

[http://www.lattice2013.uni-mainz.de/presentations/Plenaries%20Saturday/
Kuti.pdf](http://www.lattice2013.uni-mainz.de/presentations/Plenaries%20Saturday/Kuti.pdf)

COMPOSITENESS CONSTRAINTS AND CONSEQUENCES

“scaled up QCD” a la Naive Technicolor
does not work



- Close to conformal boundary spectrum may be **very different** to QCD
- Look for “Generic” Mechanism to satisfy LHC constraints.
- Experimentally viable Low Energy Near Conformal Physics of Effective Theory maybe “universal” as suggested by AdS strong coupling duality

SUPER QCD

N=1 SYM analog of pure gauge YM. For SQCD: add Nf flavors of (quark+ (scalar)quark) in fundamental rep.

Goals: condensates and spectrum (Seiberg ..)

Using DWF show (J.Giedt et. al PRD78 081781 2008) that a supersymmetric continuum limit only requires tuning of O(2-6) couplings in scalar sector

$$(N_c + 1) \leq N_f < \frac{3}{2}N_c$$

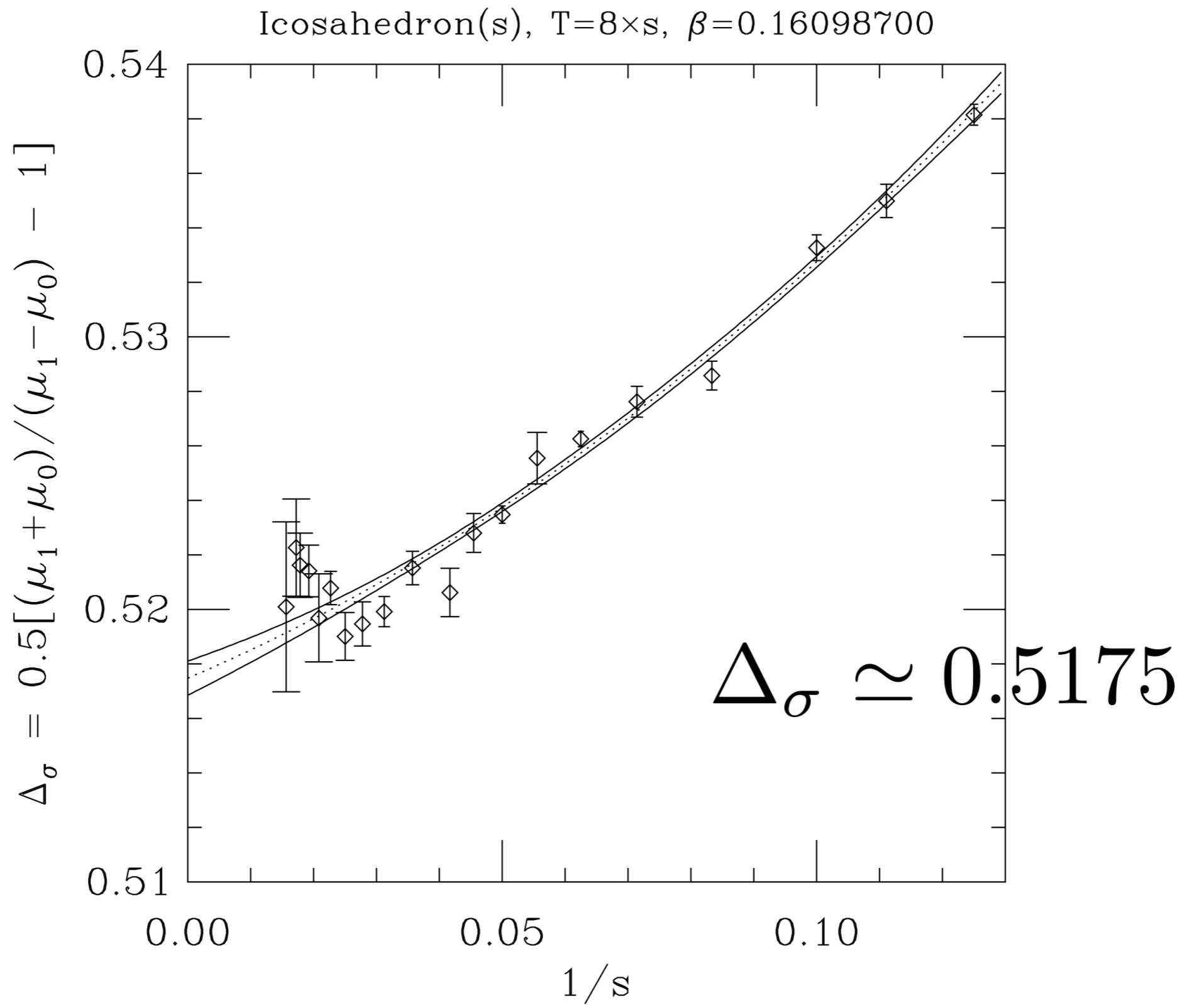
Metastable vacua expected for

Eg. 4 flavors $N_c=3$

SEXTET MODEL

- $N_f=2$ fermions in symmetric rep of $SU(3)$.
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- 3GB eaten by W, Z
- 2-loop calcs support proximity to conformal window.

Current Fit:



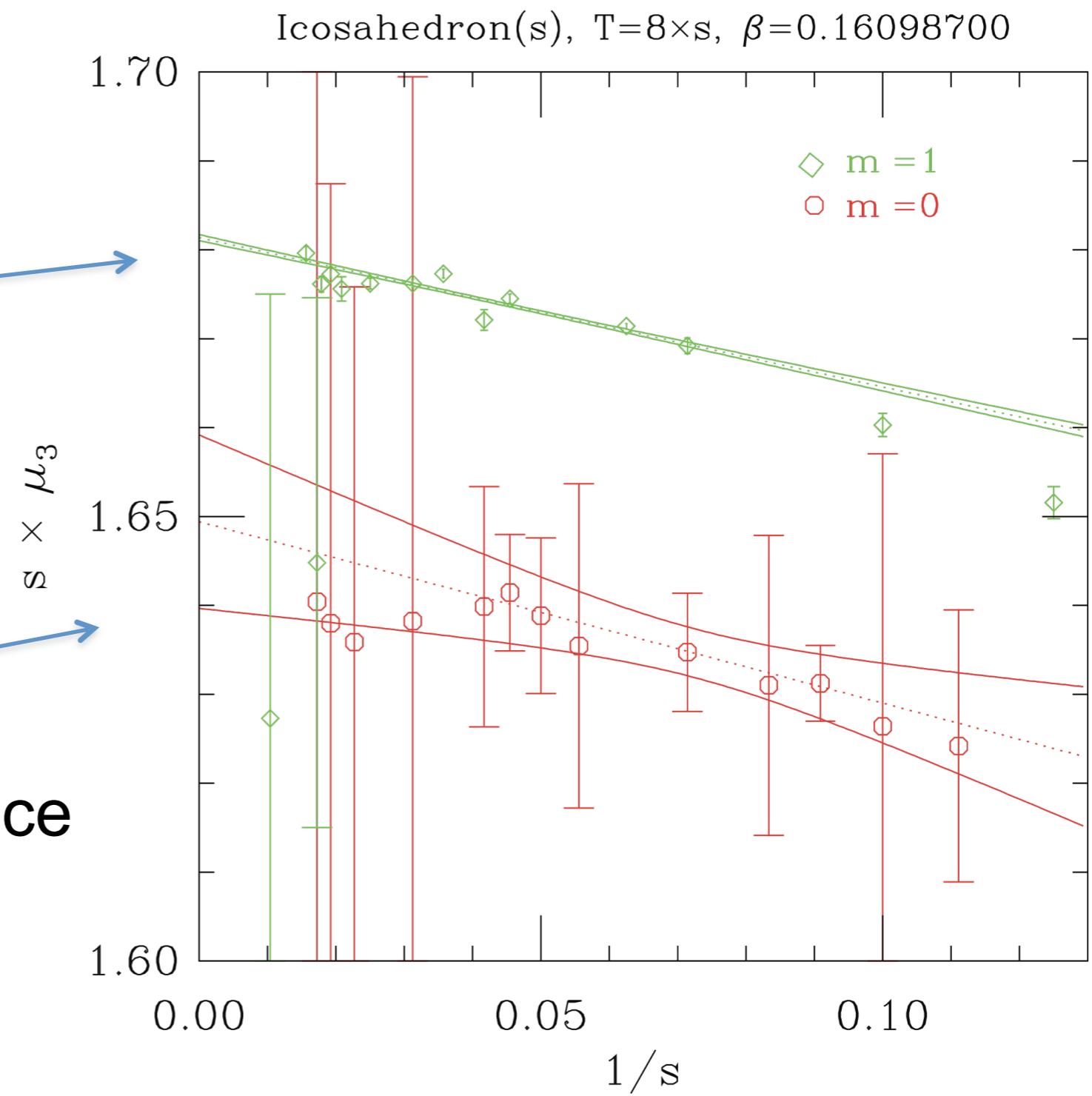
Wrong Theory?

Failure to recover $O(4,1)$ at $l = 3$?

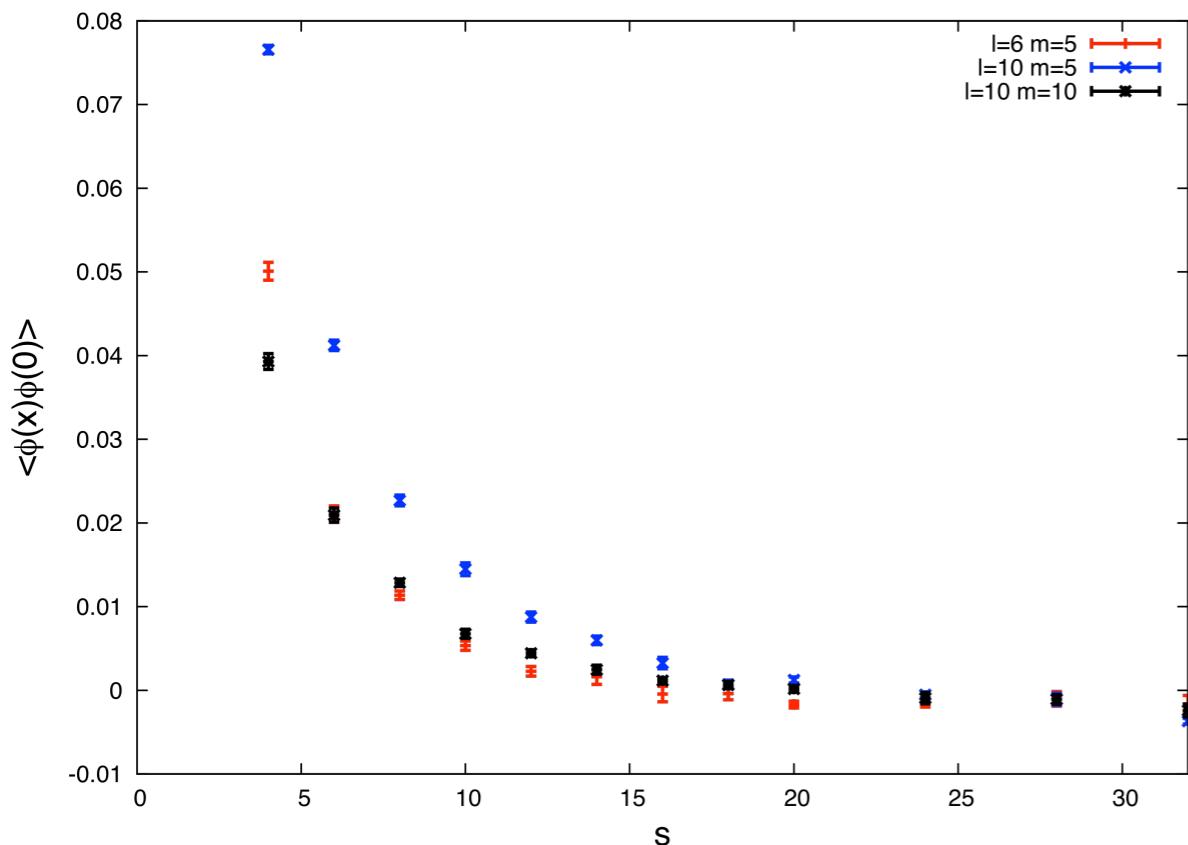
G rep

T2 rep

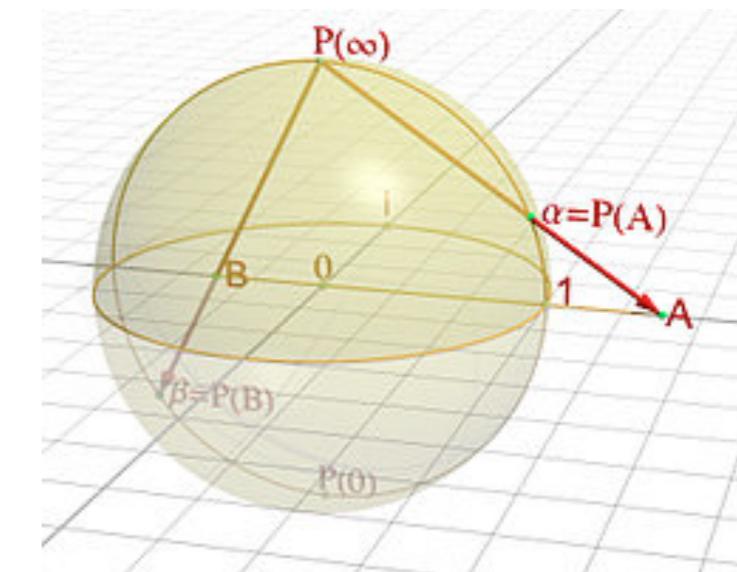
Apparent lack of convergence
to a single $O(3)$ irreducible
representation for $l = 3$



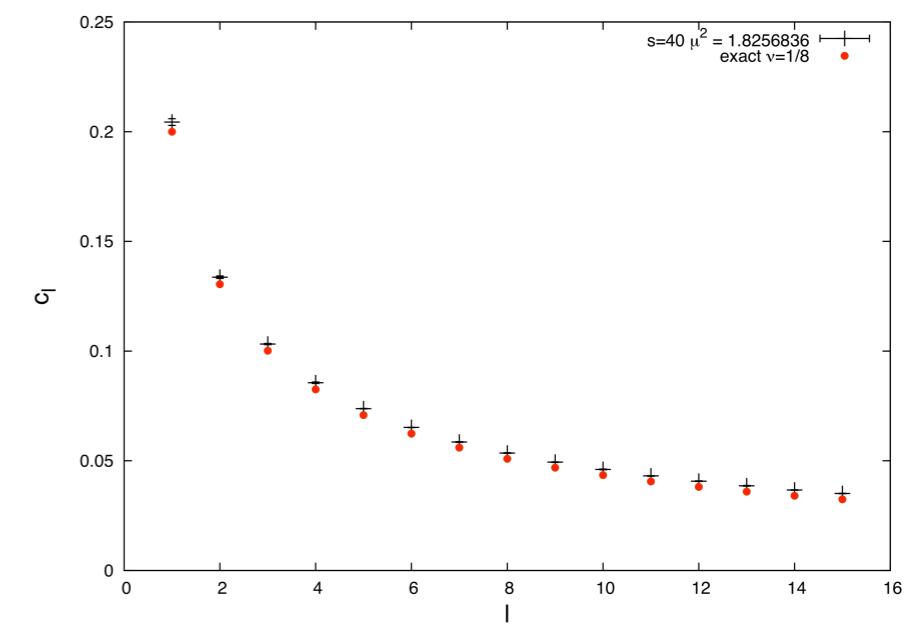
2D test on Conformal Projection to Riemann Sphere



$$\langle \phi(x_1) \phi(x_2) \rangle = \frac{1}{|x_1 - x_2|^{2\Delta}} \rightarrow \frac{1}{|1 - \cos\theta_{12}|^\Delta}$$



$$\Delta_\sigma = \eta/2 = 1/8 \simeq 0.128$$



Future? Broken 4D CFT for BSM physics,
Twisted Graphene sheets , Ads dual ?